Crisis in Semileptonic Heavy Meson Decays

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What constitutes a “crisis” in physics

- A friend who needs help?
- An unexpected result? (this can be a good kind of crisis to have)
- Contradictory results?
- An unexplainable result?
- All of the above
- None of the above

(In this talk, we may see hints of the 1st four…)

In 2002 FOCUS published a result…

- But it sort of disagreed with a result that was published at almost the same time
- But FOCUS found something in the decay that other experiments only saw hints of
- So FOCUS took a little more time in publishing everything about this decay
- But the difference remained…
- And there were other things that were interesting

What is a particle decay?

A transition of a particle from one (*initial*) state to another (*final*) state (consisting of more particles) – as described by Fermi's Golden Rule:

$$\begin{bmatrix} Transition \\ Rate \end{bmatrix} = \begin{Bmatrix} Universal \\ Coupling \end{Bmatrix} \begin{Bmatrix} Matrix \\ Element \end{Bmatrix} \begin{Bmatrix} Phase \\ Space \end{Bmatrix}$$

But a particle *lifetime* is governed by the Total Transition Rate which includes all possible states (i.e. we don't get different lifetimes for the same *initial* particle by measuring different *final* states unless very special physics is involved)

Another way to look at this:

- Even though different initial states (particles) can have different lifetimes, decay rates for individual transitions can be almost the same if the physics (matrix element) and the phase space ("Q") are similar!

$$\frac{\%A \rightarrow ZX}{Lifetime\ A} \approx \frac{\%C \rightarrow YX}{Lifetime\ C} \quad \left\{ \begin{matrix} C \sim A, Z \sim Y \\ Lifetime\ A \neq C \end{matrix} \right\}$$

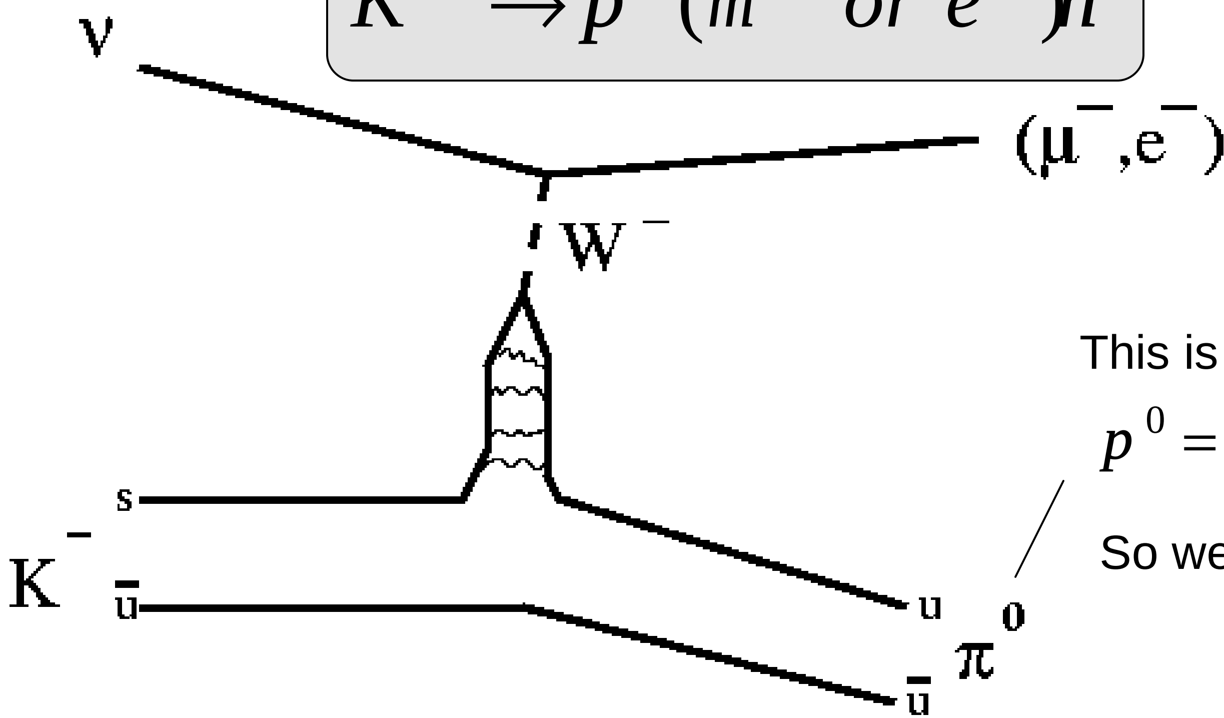
A powerful check for states with great similarities

A simple case

- Semileptonic Pseudoscalar Meson decay

- Hadronic current tends to be simpler and quasi-free of final state interactions

$$K^- \rightarrow p^0 (m^- \ or \ e^-) \bar{n}$$

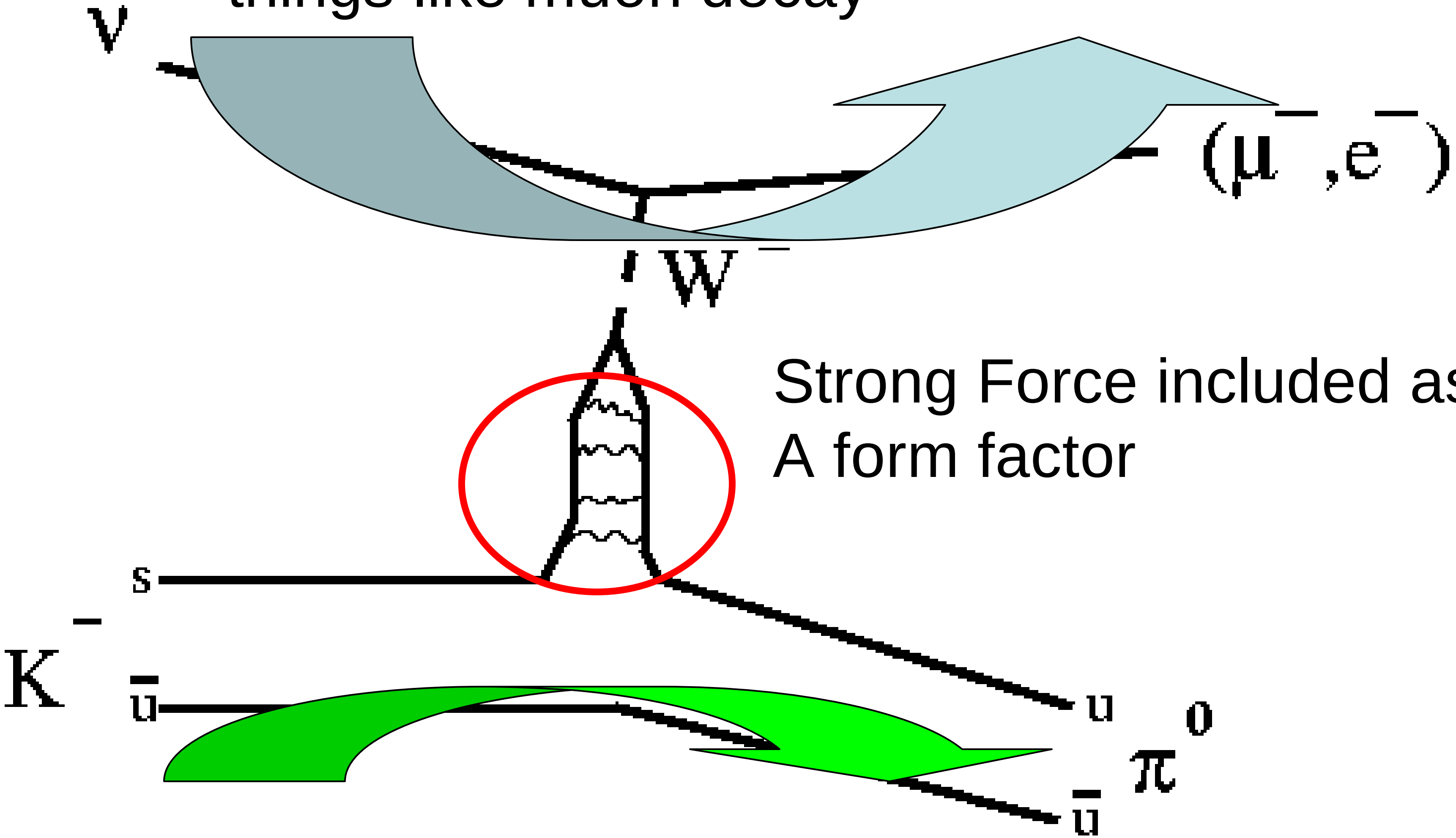


This is actually a combo:

$$p^0 = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$$

So we only get half…

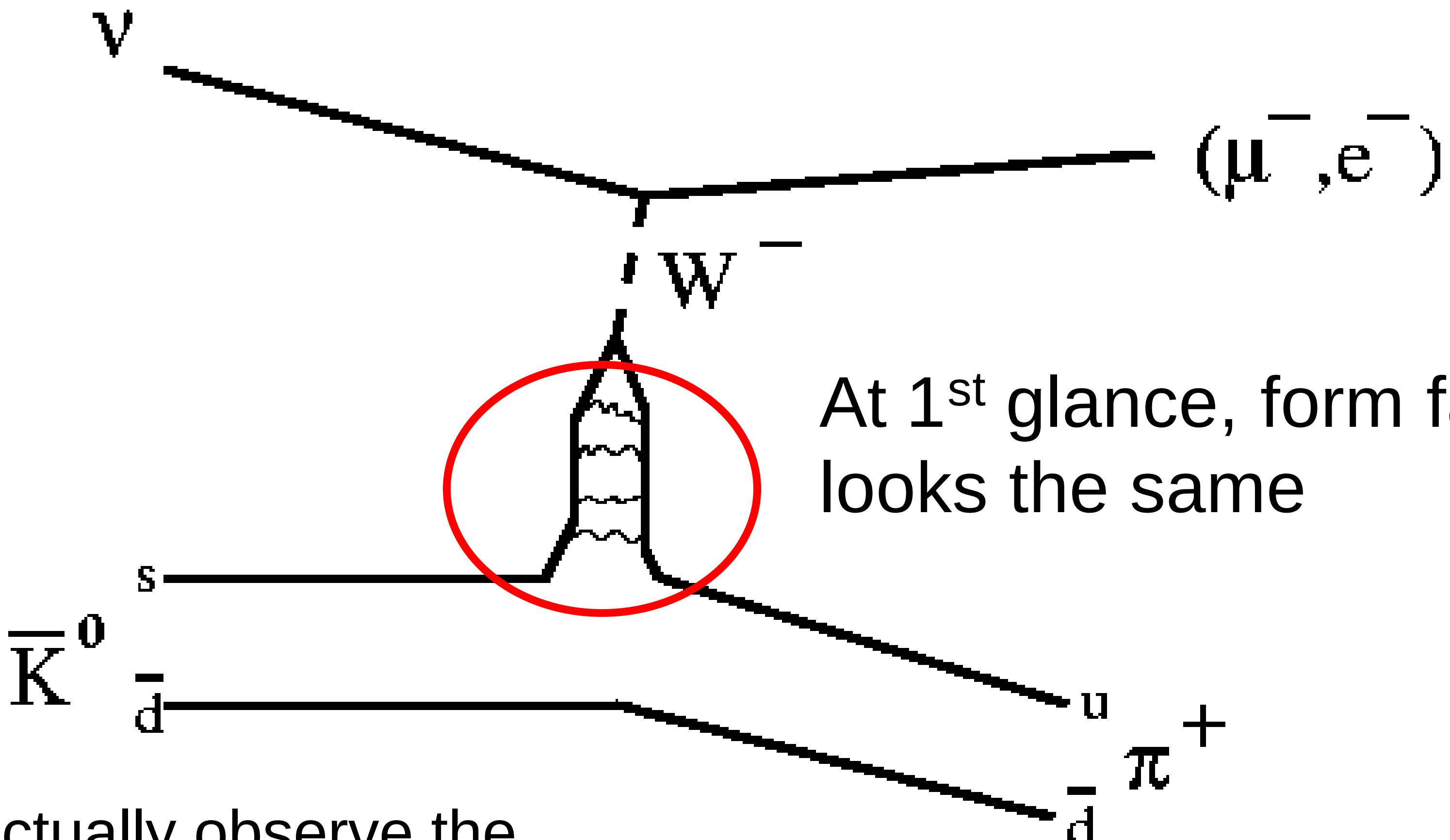
Weak current is well understood from things like muon decay



Strong Force included as A form factor

Other quark in the decay acts as a “Spectator”

Similar Decay to compare: $\overline{K}^0 \rightarrow p^+ (m^- \ or \ e^-) \overline{n}$



At 1st glance, form factor looks the same

We actually observe the neutral kaon as an admixture of particle and anti-particle. With long and sort lifetimes.

But in the bottom line, we've changed a d for a u

Lets do a comparison

	$K^{+/-}$	K^0_{long}	π^+	π^0	μ^+	e^+	ν
Mass(MeV)	494	498	140	135	106	0.511	~0
Lifetime(ns)	12.4	51.8	26.0	~0	2200	stable	'stable'

$$M(K^{\pm}) - M(\pi^0) = 359 MeV \qquad M(K_L^0) - M(\pi^{\pm}) = 358 MeV$$

$$\%(K_L^0 \to \pi^{\mp}(\mu^{\pm}\ or\ e^{\pm})\nu) = 38.81 e,\ 27.19 \mu$$

$$\%(K^{\pm} \to \pi^0(\mu^{\pm}\ or\ e^{\pm})\nu) = 4.87 e,\ 3.27 \mu$$

Notice % electron modes > % muon modes

-Muons eat Q (expect muons~2/3 electron modes)

-and effects proportional to M(lepton)^2 (few percent effect)

End up with….

Experiment | "Theory"

$$\frac{\% K_L^0(m)}{\% K_L^0(e)} = 0.70 \pm 0.01$$

0.67

$$\frac{\% K^+(m)}{\% K^+(e)} = 0.67 \pm 0.01$$

0.67

$$(1/2)\frac{\% K_L^0(e) t_+}{\% K^+(e) t_L} = 0.953 \pm 0.016$$

0.97

$$(1/2)\frac{\% K_L^0(m) t_+}{\% K^+(m) t_L} = 0.994 \pm 0.022$$

0.97

$$\frac{\% K_L^0(e) t_S}{\% K_S^0(e) t_L} = \frac{(38.81)(0.08958\, ns)}{(0.069)(51.8\, ns)} = 0.97 \pm 0.06$$

This better be close to 1!

This is complicated stuff

- Lots of model corrections on the order of 1%
- Used to find V_{us} CKM angle (Part of the coupling)
- Discrepancy appears to be in neutral kaon
- Combine carefully with other: V_{ud} V_{ub} ...Get

Expect: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

$$(2002\ PDG\ Estimates) = 0.9957 \pm 0.0019\ (2002)$$

$$(2004\ PDG\ Estimates) = 0.9967 \pm 0.0015\ (2004)$$

Find a greater than 2 sigma discrepancy!

Other Heavy Mesons decay too

Approximately

$$\Gamma_e \propto M_{Heavy}^5 (1 - 2(M_{Light} / M_{Heavy}))$$

And (at most!) $dM_{Heavy} \sim dM_{light} \sim 5\,Mev$

Expect differences to get smaller for similar light/heavy ratio with increasingly heavier mesons when we change an up for a down quark

$$(M(D^+)/M(D^0))^5 = 1.01$$

$$(M(B^+)/M(B^0))^5 = 1.00$$

And Expect

$$\Gamma D^+(e,m)/\Gamma D^0(e,m) = 1.01$$

$$\Gamma B^+(e,m)/\Gamma B^0(e,m) = 1.0$$

$$\Gamma D(m)/\Gamma D(e) = 0.98 - 0.97$$

$$\Gamma B(m)/\Gamma B(e) = 0.996$$

And the case is fine for B's

$$\Gamma B^0(e,m)/\Gamma B^+(e,m) = 1.08 \pm 0.15$$

But Charm mesons are interesting!

$$\Gamma D^+(e)/\Gamma D^0(e) = 0.74 \pm 0.11$$

Another >2 sigma effect!

$$\Gamma D^+(m)/\Gamma D^0(m) = 0.87 \pm 0.31$$

$$\Gamma D^0(m)/\Gamma D^0(e) = 0.89 \pm 0.06$$

$$\Gamma D^+(m)/\Gamma D^+(e) = 1.0 \pm 0.38$$

Errors are too big to tell

How do we increase our Charm?

- Where's the biggest error coming from?

$$\%(D^0 \rightarrow K^- e^+ n) = 3.58 \pm 0.18$$

$$\%(D^0 \rightarrow K^- m^+ n) = 3.19 \pm 0.17$$

$$t\,(D^0) = 410.3 \pm 1.5\ ps$$

$$\%(D^+ \rightarrow \overline{K}^0 e^+ n) = 6.7 \pm 0.9$$

$$\%(D^+ \rightarrow \overline{K}^0 m^+ n) = 7.0 \pm 2.5$$

Best Candidates!

$$t\,(D^+) = 1040 \pm 7\ fs$$

Is there anything else that helps?

- Charm and Beauty mesons have a lot more mass than kaons, so there are more decay possibilities
- In fact, earlier models predicted that:

$$\Gamma(D \to Ken) \approx \Gamma(D \to K^{*}en)$$

Lowest excited Kaon state

-But Experiments throughout the 90's were seeing

$$\frac{\Gamma(D \to K^{*}en)}{\Gamma(D \to Ken)} \approx 0.5$$

So in 2002, a new measurement:

$$\frac{\%D^{+} \rightarrow \overline{K}^{*} e^{+} n}{\%D^{+} \rightarrow \overline{K}^{0} e^{+} n} = 0.99 \pm 0.06 \pm 0.07$$

- Got me pretty excited
- And a friend of mine got pretty excited because if you compared his measurement to theirs:

$$\frac{\%D^{+} \rightarrow \overline{K}^{*} m^{+} n}{\%D^{+} \rightarrow \overline{K}^{*} e^{+} n} = 1.23 \pm 0.12$$

And 0.95 was expected

And I was especially excited…

- Since I was working on a measurement of:

$$\frac{\%D^{+} \rightarrow \overline{K}^{*0} m^{+} n}{\%D^{+} \rightarrow \overline{K}^{0} m^{+} n}$$

- And about half of the previous experiments that compared rates from D^+ and D^0 just assumed:

$$\Gamma(D^{+} \rightarrow \overline{K}^{*0}(m \;\; or \;\; e)^{+} n) = \Gamma(D^{0} \rightarrow K^{*-}(m \;\; or \;\; e)^{+} n), \quad or$$

$$\Gamma(D^{+} \rightarrow \overline{K}^{0}(m \;\; or \;\; e)^{+} n) = \Gamma(D^{0} \rightarrow K^{-}(m \;\; or \;\; e)^{+} n)$$

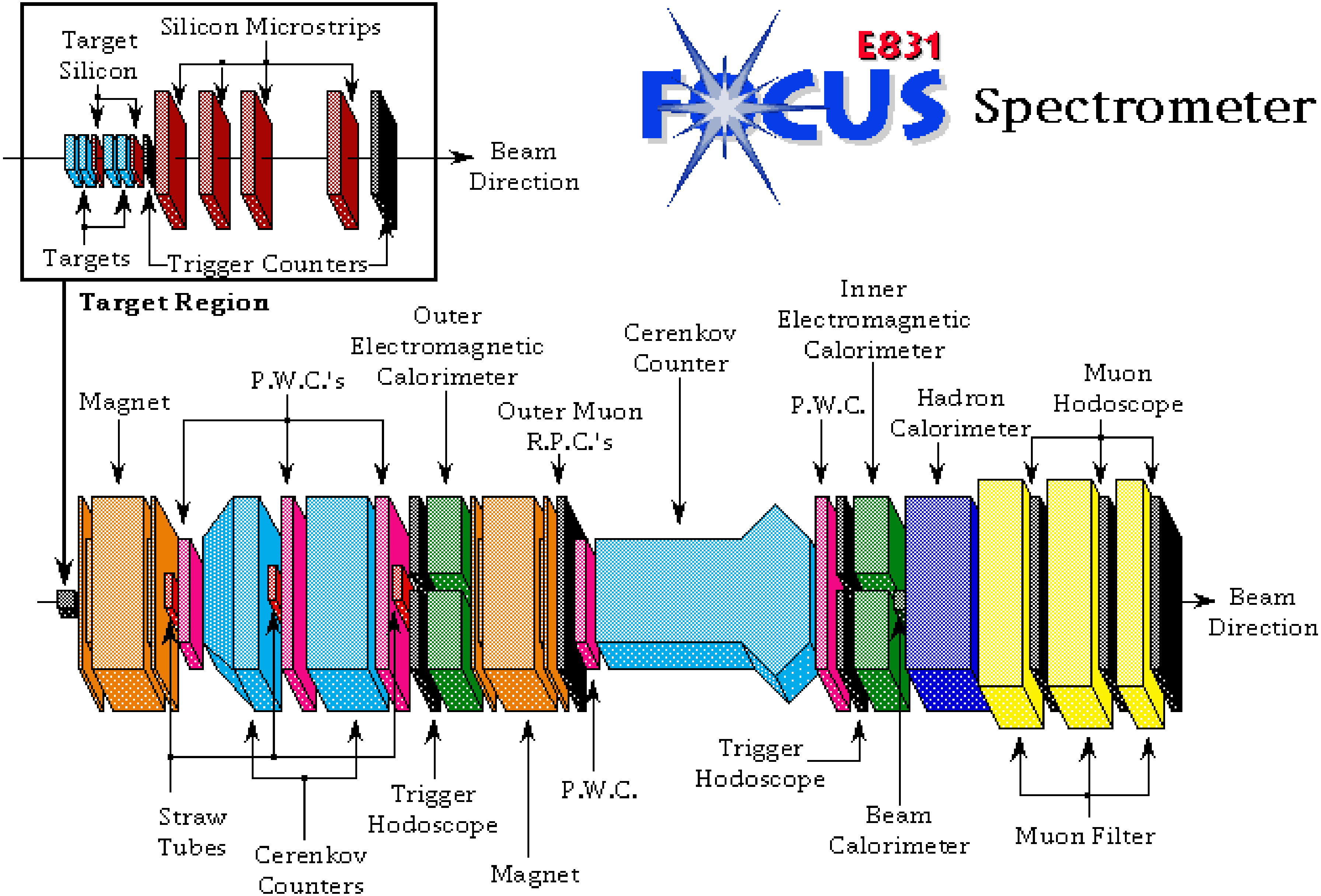
Including me in my thesis ….(This is a crisis!)

So how do you measure this?

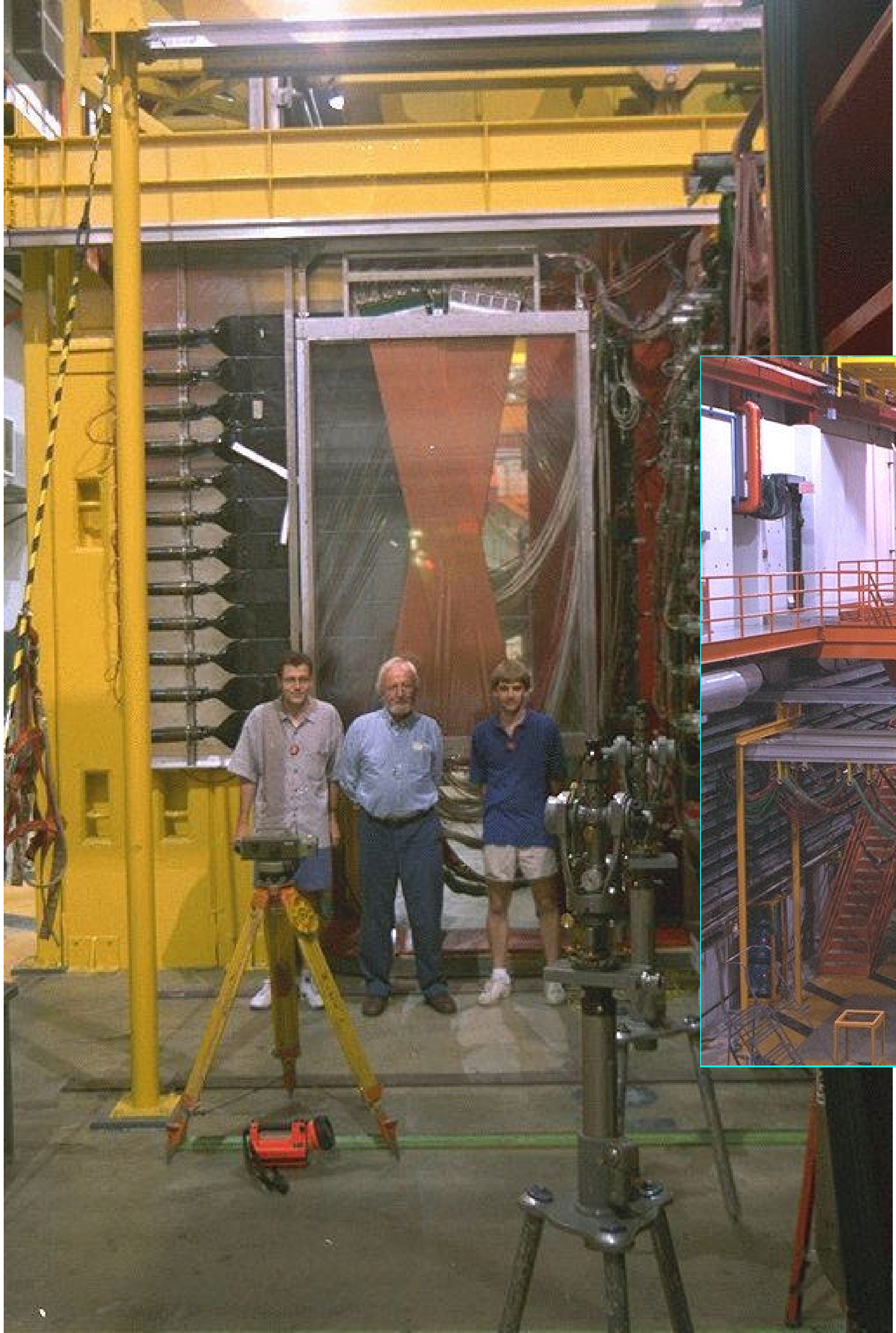
- Since the shorter lived neutral kaon and the excited neutral kaon decay into 2 charged tracks at a very predictable rate, the systematic errors, which are prevalent when comparing decays with different track multiplicities or decays containing reconstructed neutrals in only one state, will tend to be smaller… Blah blah blah

You try to pick decays which have similar topologies and compare them

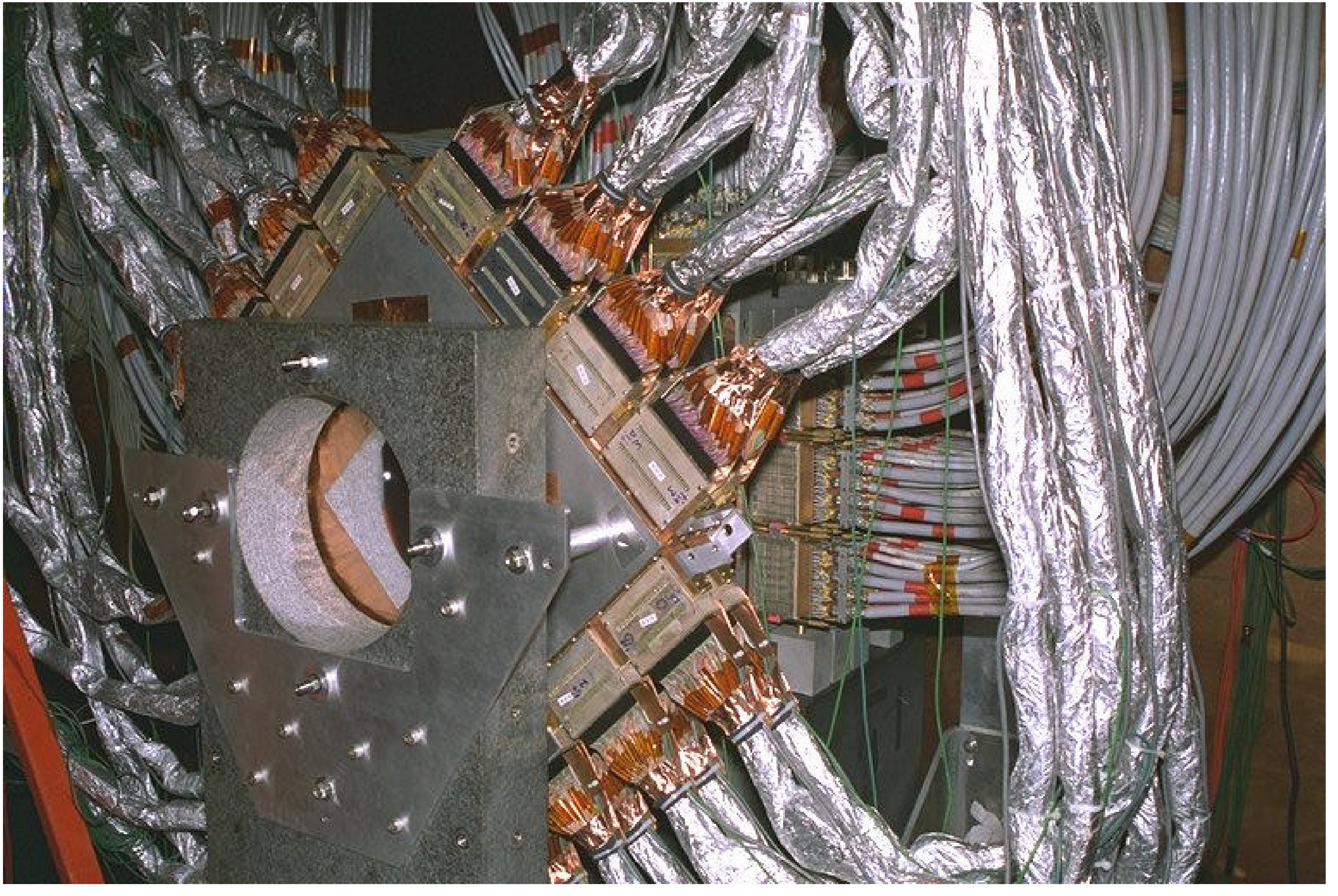
Because Experiments are Complex



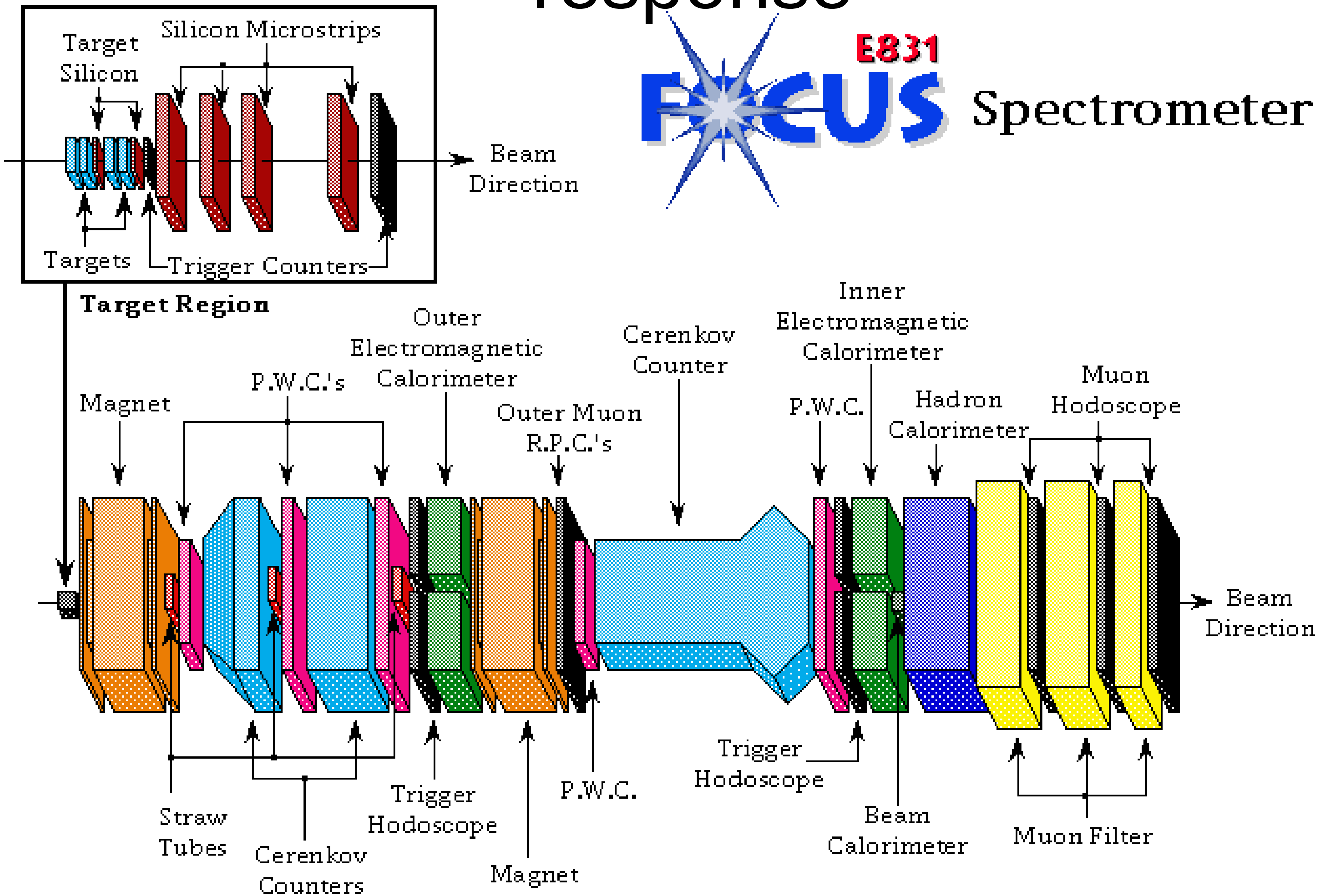
Big



And did I mention Complex?

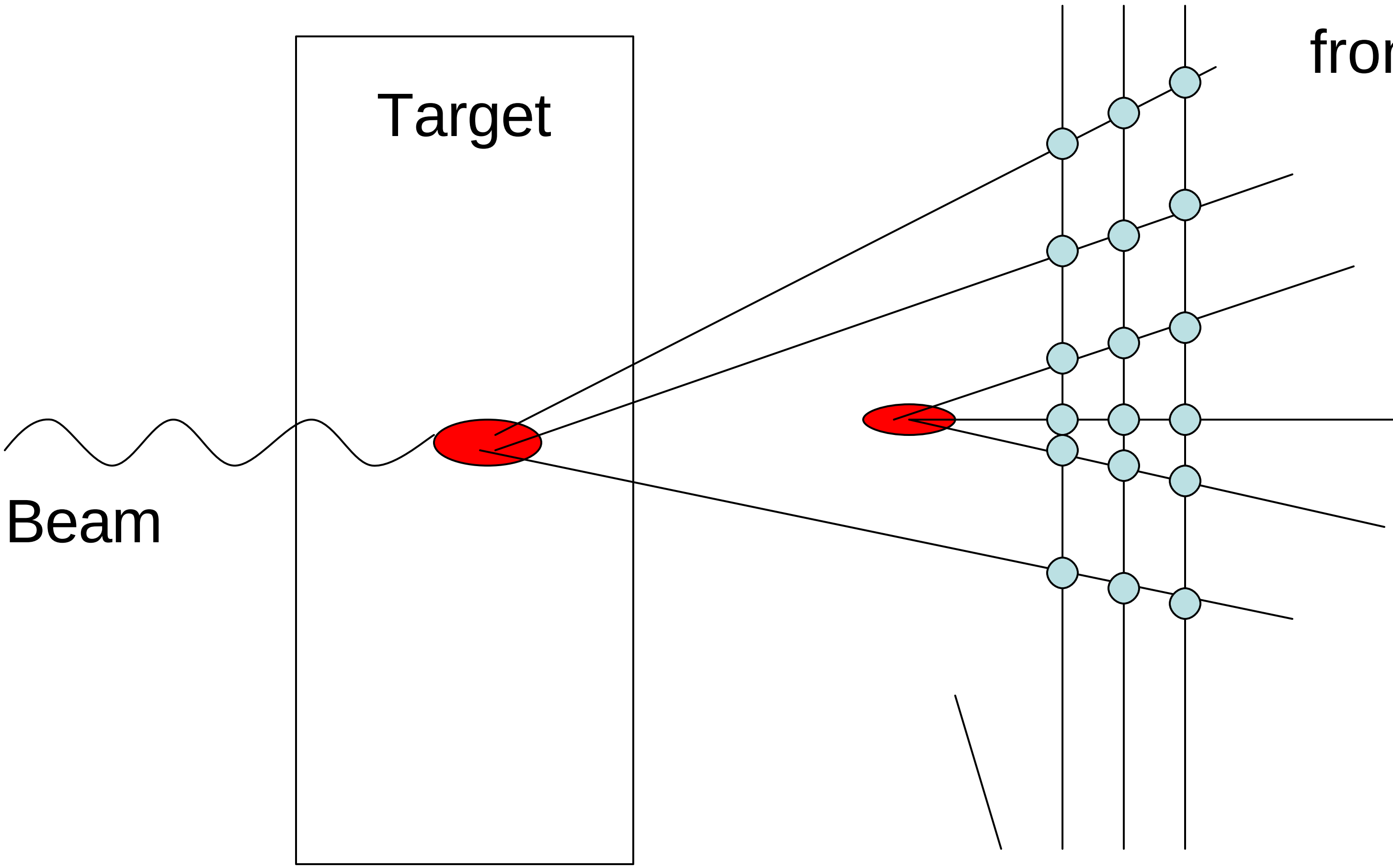


So you need to simulate the detector response



Signature of Charm Mesons

Hits in detector planes from the tracks



Connect The Dots!

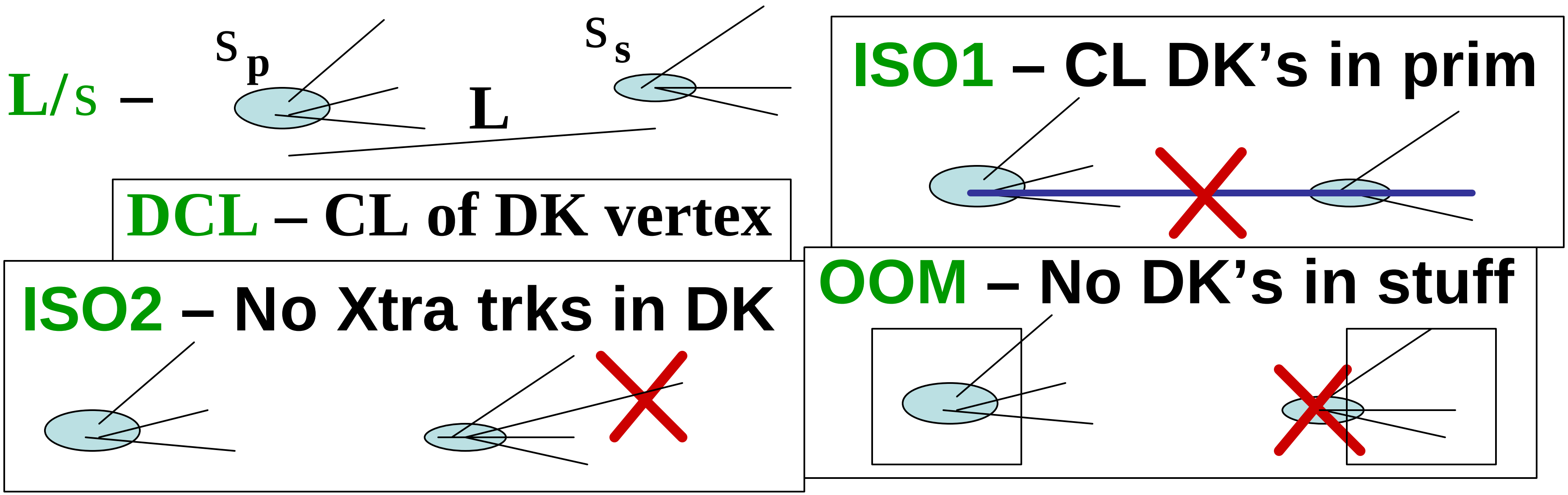
Primary Interaction in Target make tracks

Since the D meson is moving very nearly the speed of light, a 1 ps lifetime becomes ~1 cm of travel

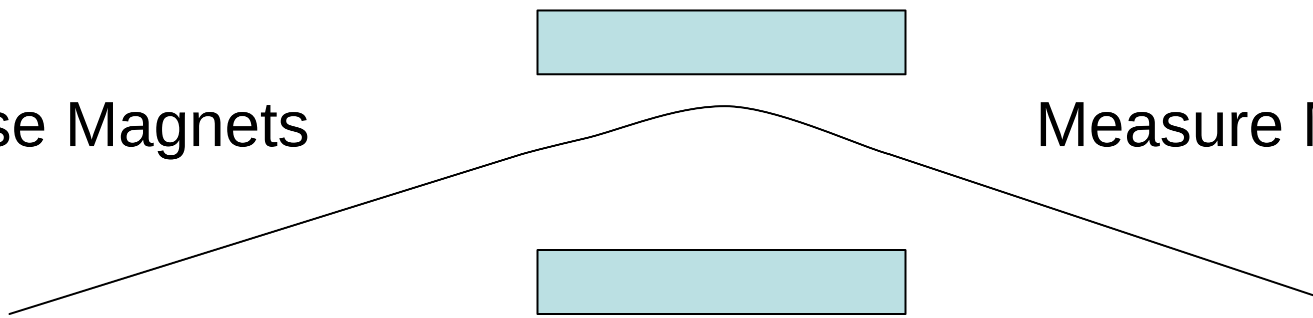
And you can do lots with tracks

Vertexing “cuts”:

$$D^+ \to (p,K)m^+n$$

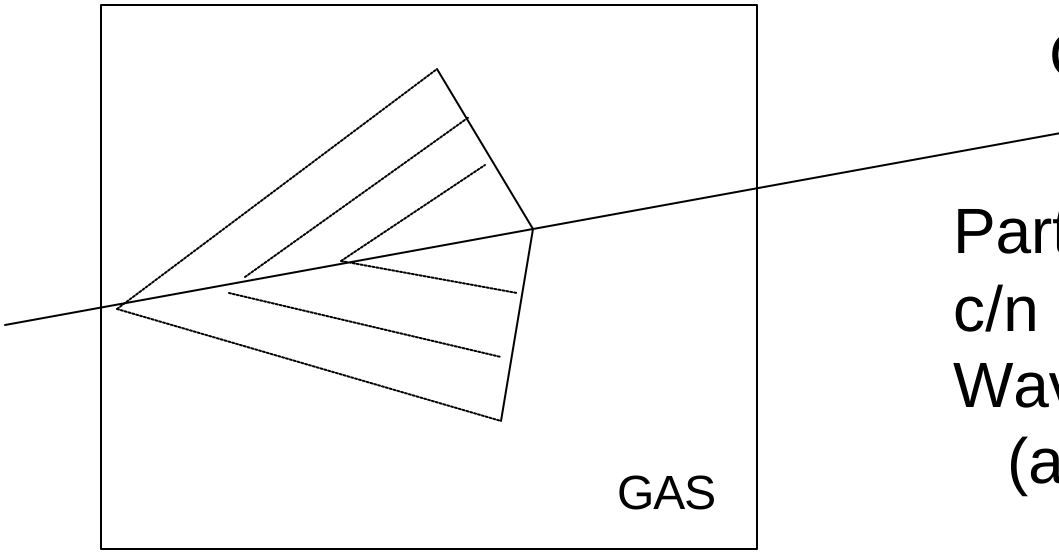


Use Magnets



Measure Momentum

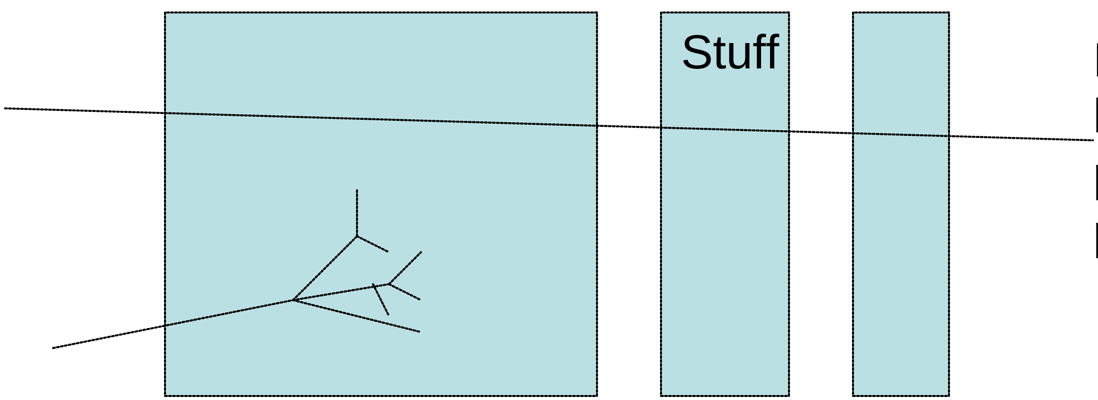
Signature of other particles



Cherenkov Detectors

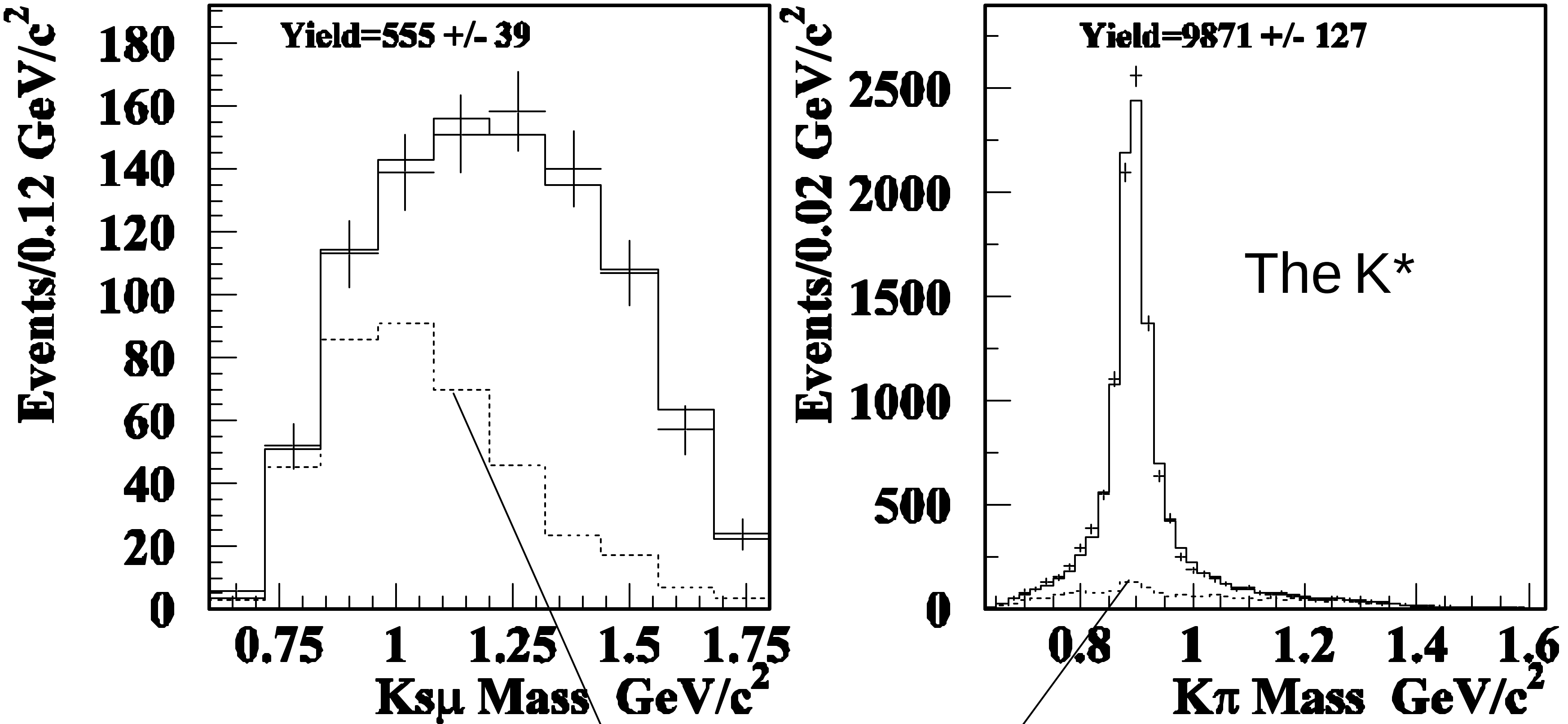
Particles moving faster than c/n in a gas, make a "shock Wave" of light (Mass sensitive) (assuming n(λ) is ~constant)

Muon Detectors



Muons have a much higher chance of penetrating material than paons, pions, electrons…

Form invariant Quantities (Mass)



Since Ks decays into
2 pions, this is the mass
of the 2 pions and a muon

Estimate Backgrounds

(Interesting since K* can decay into a Kshort and a neutral pion as well as a charged kaon and a charged pion

And be especially careful!

- The K* has a lifetime < 10^{-20}s
- But the Kshort has a lifetime of 90 ps

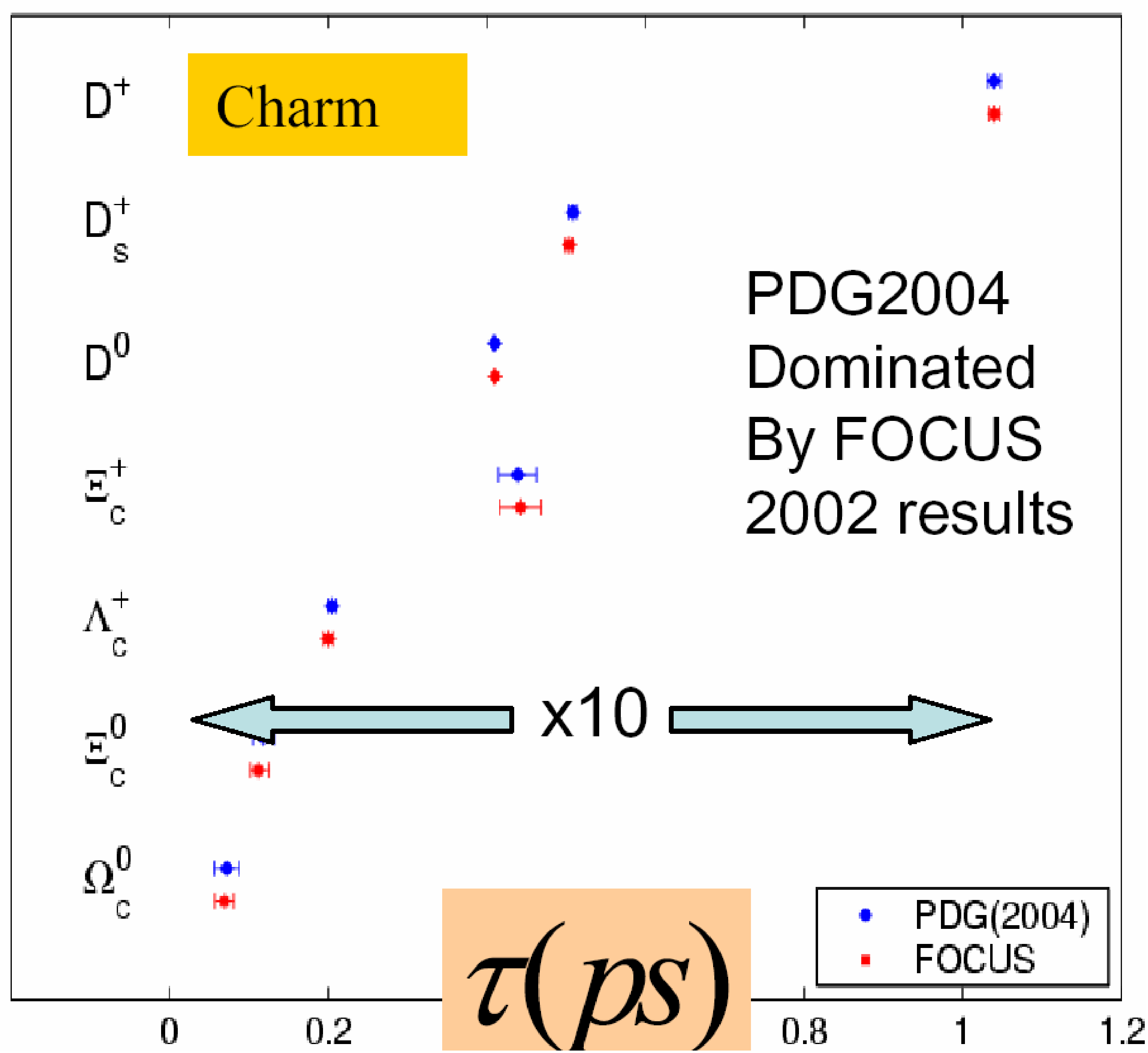
Only a fraction of the Kshorts decay in the same area as the D meson

But that fraction is in a VERY well understood part of the detector….

Because the super strength of FOCUS is the measurement of short lifetimes

FOCUS Lifetimes Comparison

From ICHEP04 talk by Ian Shipsey



But to be sure, you vary lots of things, and see the effect on the ratio

Systematic Contribution	Value
Normalized K_S^0 Mass Cut	0.008
Secondary Vertex Location	0.017
K_S^0 Vertex Location	0.013
Muon Magnet Consistency	0.012
Muon Momentum Cut	0.008
$M_{\rm pole}$ and f_-/f_+ variation	0.015
Contribution from fit variations	0.013
S-wave Fraction (K^* ratio only)	0.003

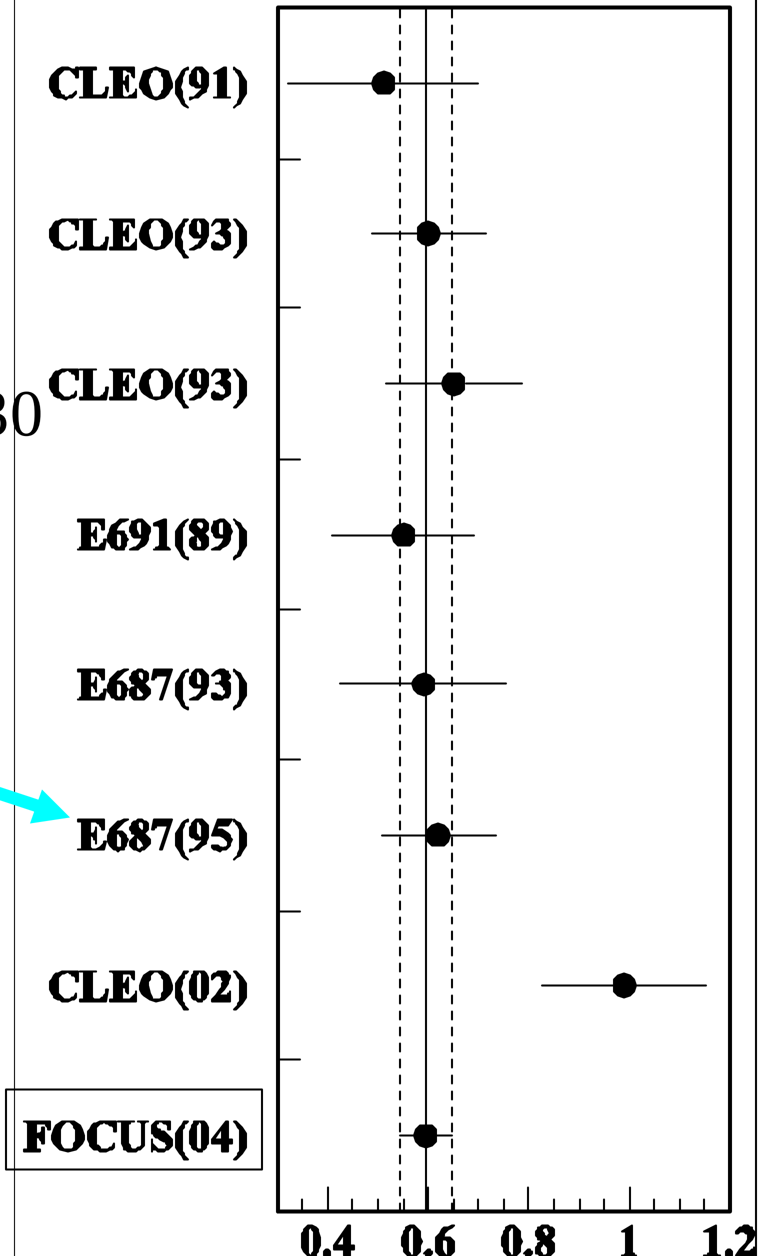
So you can compare with confidence

Final FOCUS(04) Result:

$$\frac{D^+ \to \overline{K}^{*0} m^+ n}{D^+ \to \overline{K}^{0} m^+ n} = 0.594 \pm 0.043 \pm 0.030$$

Old Thesis Paper:

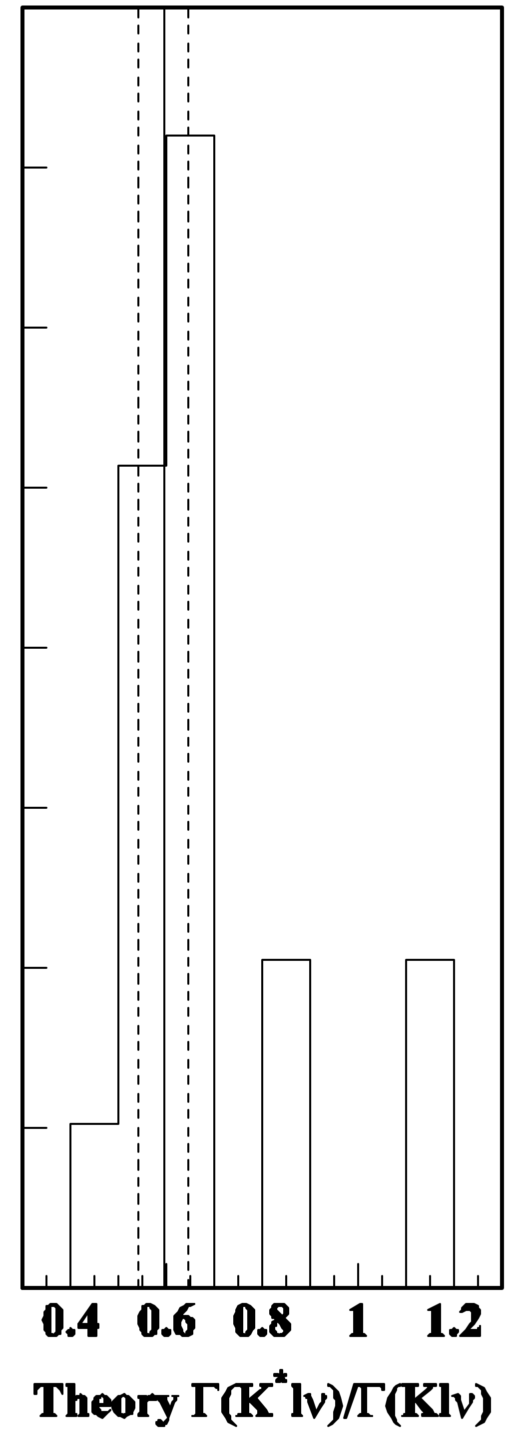
$$\frac{\Gamma(D^+ \to \overline{K}^{*0} m^+ n)}{\Gamma(D^0 \to K^- m^+ n)} = 0.62 \pm 0.11$$



Looks like ratio is
closer to 0.5 again

And Compare to Models etc.

Models cluster around the data results



$$\Gamma D^{+}(m)/\Gamma D^{+}(e) = 1.42 \pm 0.22$$

$$\Gamma D^{+}(m)/\Gamma D^{0}(m) = 1.15 \pm 0.15$$

$$\Gamma D^{+}(m)/\Gamma D^{0}(e) = 1.02 \pm 0.13$$

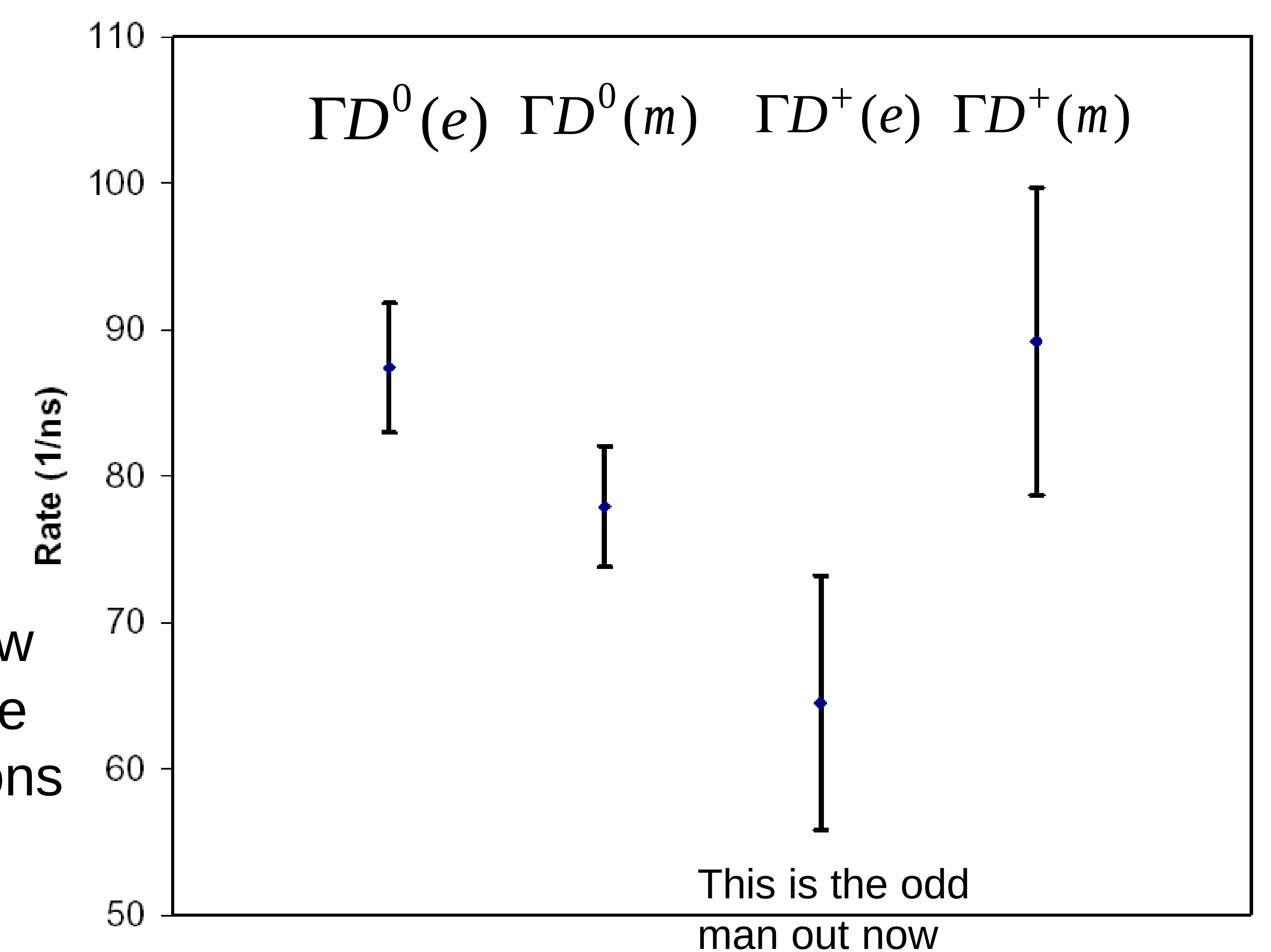
New result agrees with neutral D meson

Experiment	Quantity	Result
CLEO(91)[5]	$\frac{\Gamma(D^0 \to K^{*-} e^+ \nu)}{\Gamma(D^0 \to K^- e^+ \nu)}$	$0.51 \pm 0.18 \pm 0.06$
CLEO(93)[6]	$\frac{\Gamma(D^0 \to K^{*-} e^+ \nu)}{\Gamma(D^0 \to K^- e^+ \nu)}$	$0.60 \pm 0.09 \pm 0.07$
CLEO(93)[6]	$\frac{\Gamma(D^+ \to \overline{K}^{*0} e^+ \nu)}{\Gamma(D^+ \to \overline{K}^0 e^+ \nu)}$	$0.65 \pm 0.09 \pm 0.10$
E691(89)[13]	$\frac{\Gamma(D^+ \to \overline{K}^{*0} e^+ \nu)}{\Gamma(D^0 \to K^- e^+ \nu)}$	0.55 ± 0.14
E687(93)[14]	$\frac{\Gamma(D^+ \to \overline{K}^{*0} \mu^+ \nu)}{\Gamma(D^0 \to K^- \mu^+ \nu)}$	$0.59 \pm 0.10 \pm 0.13$
E687(95)[15]	$\frac{\Gamma(D^+ \to \overline{K}^{*0} \mu^+ \nu)}{\Gamma(D^0 \to K^- \mu^+ \nu)}$	$0.62 \pm 0.07 \pm 0.09$
CLEO(02)[4]	$\frac{\Gamma(D^+ \to \overline{K}^{*0} e^+ \nu)}{\Gamma(D^+ \to \overline{K}^0 e^+ \nu)}$	$0.99 \pm 0.06 \pm 0.07 \pm 0.06$ (± 0.12) [a]
FOCUS(04)	$\frac{\Gamma(D^+ \to \overline{K}^{*0} \mu^+ \nu)}{\Gamma(D^+ \to \overline{K}^0 \mu^+ \nu)}$	$0.594 \pm 0.043 \pm 0.030$

[a] The PDG00 [16] error for $\Gamma(D^+ \to \overline{K}^0 \ell^+ \nu)/\Gamma_{Total}$, omitted [18] in the CLEO [4] result, is shown in parentheses.

That measurement that got everything started, wasn't really a measurement!

In terms of our original interest



Errors grow since these comparisons tend to be indirect

This is the odd man out now

And the conclusion of the analysis

- The ratio of the K*/K ratio is indeed closer to ½ than 1 (evidence is overwhelming now)
- Charged D meson rate into a kaon and and electron is probably underestimated
- Some other conclusions ancillary to this talk

(It’s in PLB 598, pg 33-41)

And then the Results started to come in from the summer conferences (and preprints)

I'm happiest about this one

- At ICHEP04 in Beijing (Jiangchuan Chen)

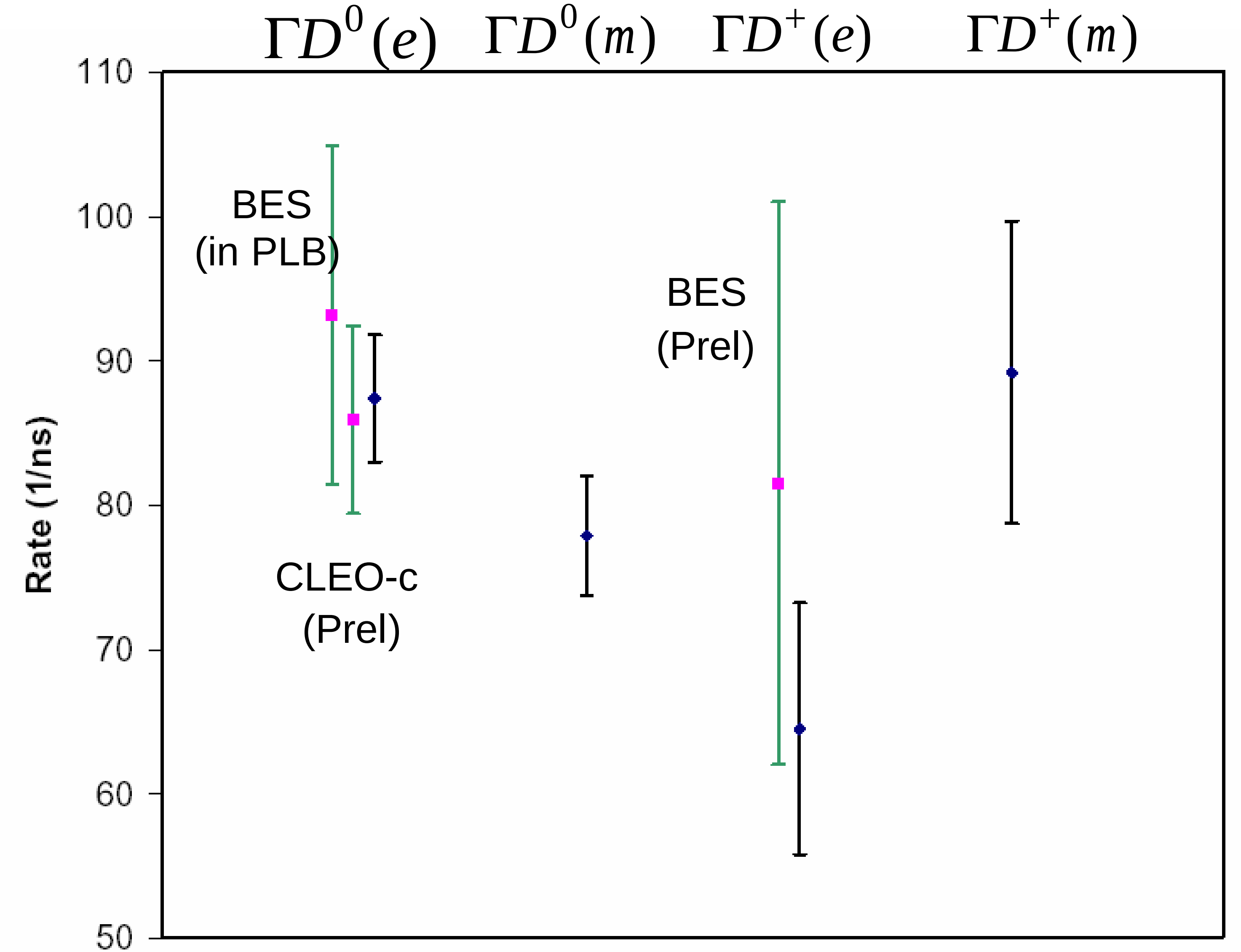
◆ Ratio of partial width

	BES	MARK III	PDG04
$\frac{\Gamma(D^0 \to K^- e^+ \nu_e)}{\Gamma(D^+ \to \overline{K}^0 e^+ \nu_e)}$	**1.15±0.29±0.09** preliminary	1.44 ± 0.62	1.4±0.2

Obtained based on the branching fractions quoted from PDG04

BES preliminary results consistent to the isospin conservation held in D meson semi-leptonic decays

And here's where they all fall.



And you might be interested to know

KTeV has done a measurement

$$\frac{\%K_L^0(m)}{\%K_L^0(e)} = 0.6640 \pm 0.0026 \ \ (new \quad pred = 0.666 \pm 0.0029)$$

Which gives:

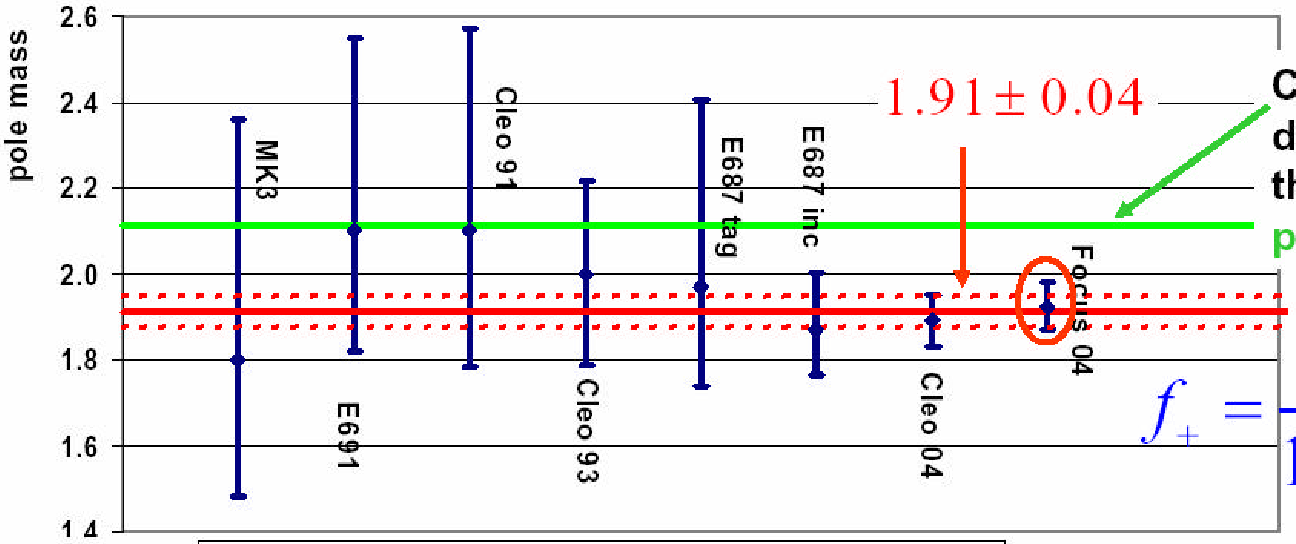
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9982 \pm 0.0019$$

And the new CLEO-c measurements give:

$$\frac{D^0 \to K^{*-} e^+ n}{D^0 \to K^- e^+ n} = 0.59 \pm 0.09$$

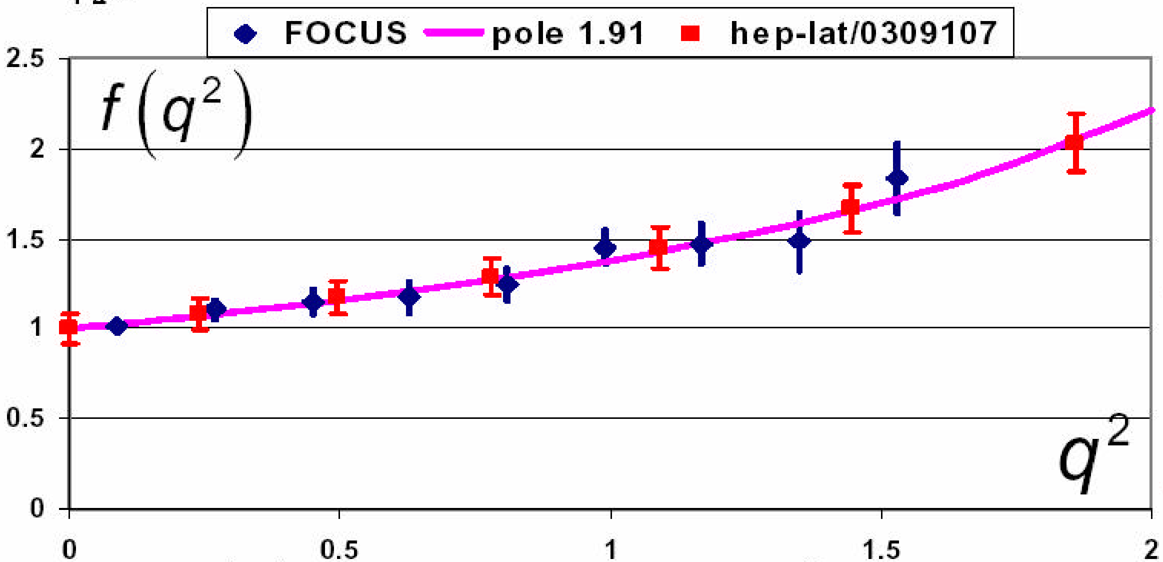
And now we are beginning to really measure the Matrix Element

Pole mass fits and LQCD calculations



Clearly the data does not favor the simple Ds* pole

$$f_+ = \frac{f_+(0)}{1 - q^2 / m^2_{\text{pole}}}$$



Agreement with LQCD unquenched calculation is also very impressive!

This calculation predicts *$f_+^{\pi}(0)/f_+^{K}(0)$=0.85 in great agreement with the FOCUS result.*

DPF04 Talk by Lorenzo Agostino

Round up and the future

>For now this charm decay crisis looks solved

(electron mode for the charged D appears low)

- The ratio of K*/K is grounded around 0.6
- Interest in these decays is accelerating!

  (Big e+/e- samples are finally appearing)

Hmmmmm…. Couplings measured in a few years!

- There’s actually more FOCUS data sitting around, and with a lot of work, the muon sample could double, and we could do e’s and maybe measure that swell matrix element…

Lot of references used in this talk

The Particle Data Group tables and summaries (2000-2004)
The ICHEP04 talks of Ian Shipsey and Jiangchuan Chen
The DPF04 talk of Lorenzo Agostino
All the references in PLB 598, pg 33-41
The Klong papers hep-ex 0406001 v1 & 0406003 v1
I'm sure to have missed a couple…

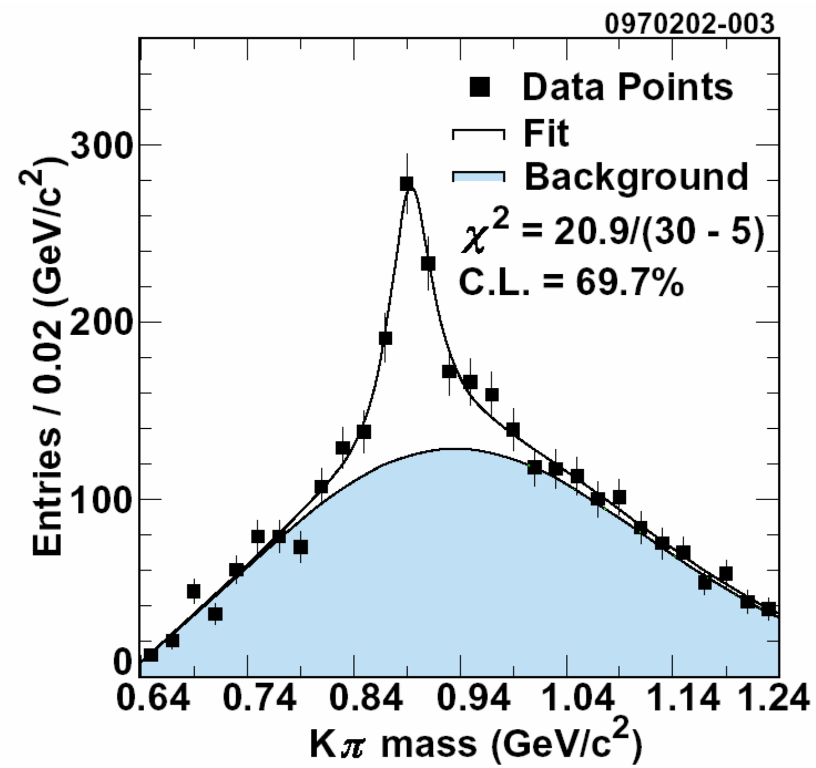
And special thanks to:

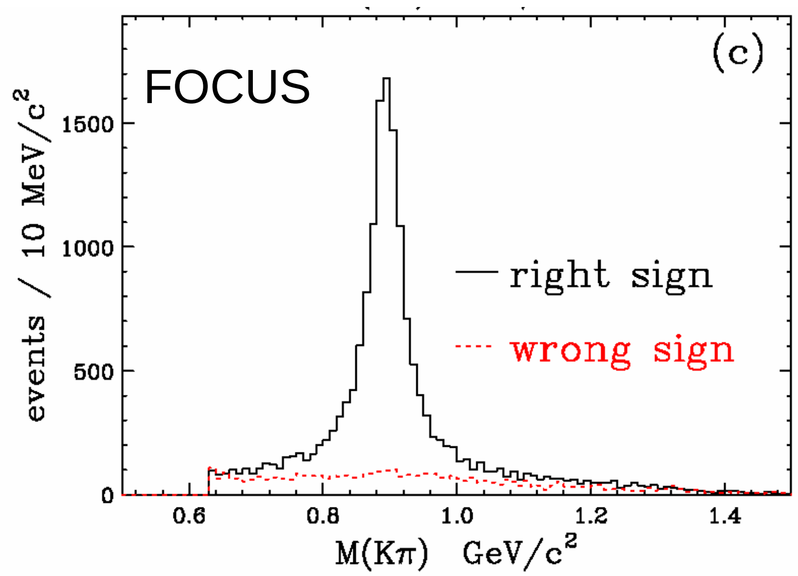
University of Colorado and Vanderbilt for supporting the sabbatical during which this work was performed

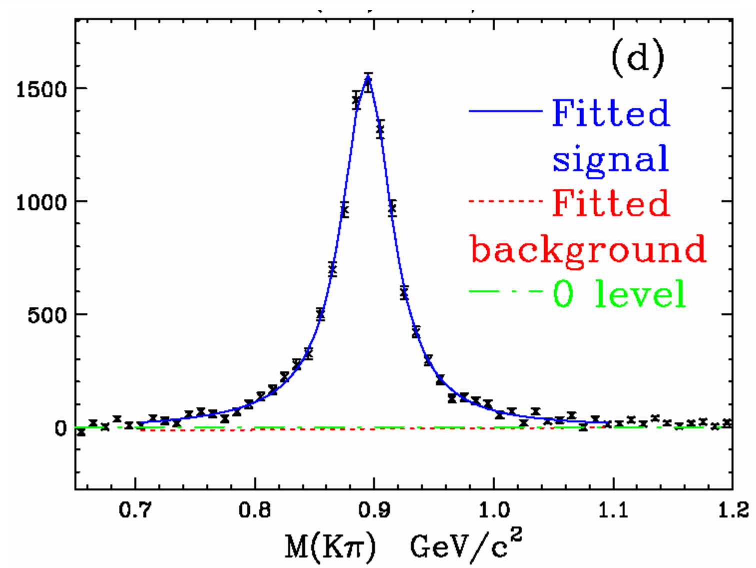
(And Cynthia for projector help)

Differences in the K* analysis

Other Experiment







Semileptonic Charm Decays

More than just CKM measurement tools…

"Simple" Equation:

(D decay, No form factors,
V decays to spin 0 particles)

$$\frac{d^2\Gamma}{d\cos q_V\, d\cos q_\ell} \propto$$

Neutrino is left handed

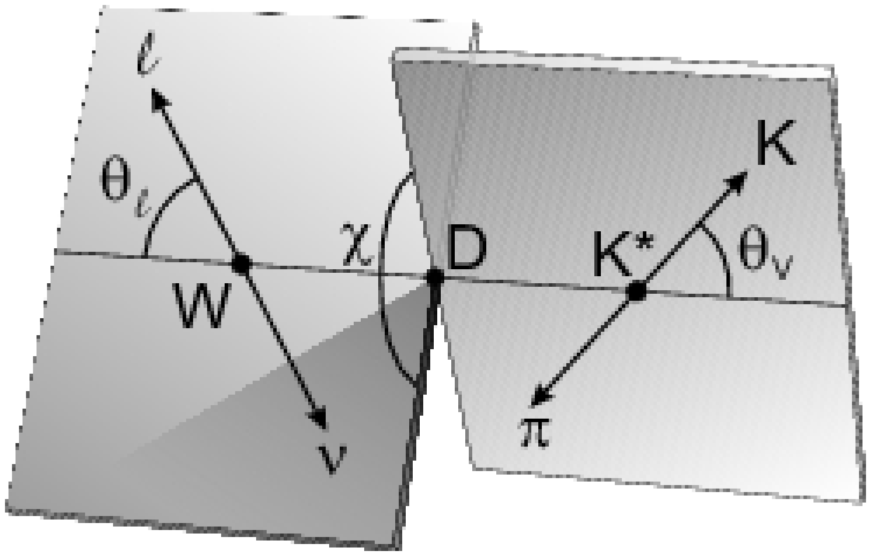
$$\{(1+\cos q_\ell)^2\Gamma_+ + (1-\cos q_\ell)^2\Gamma_-\}\sin^2 q_V$$

Prefers W spin along muon,e

$$+4\sin^2 q_\ell \cos^2 q_V \Gamma_0$$

Prefer L_Z=0

V products spinless



Gets Complicated...

Scalar Resonance?

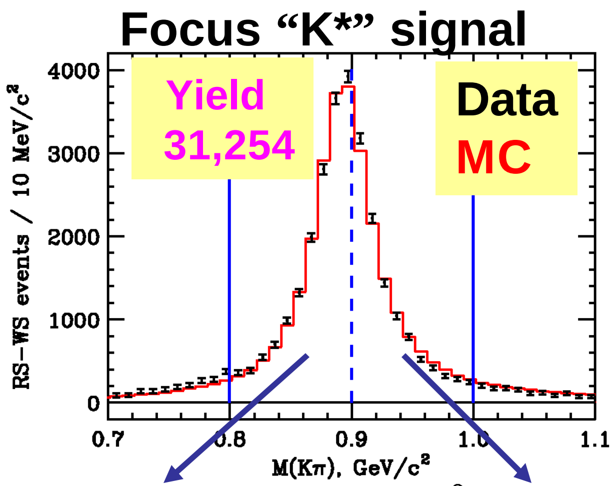
CP?

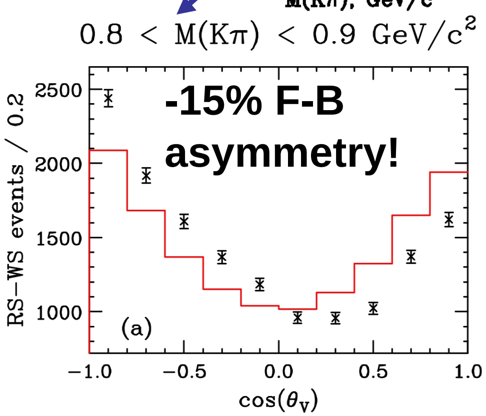
Form Factors

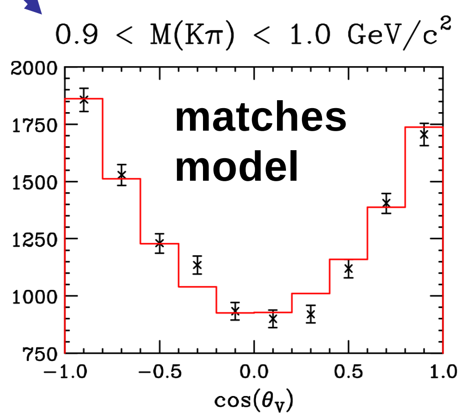
FOCUS saw discrepancies in the data

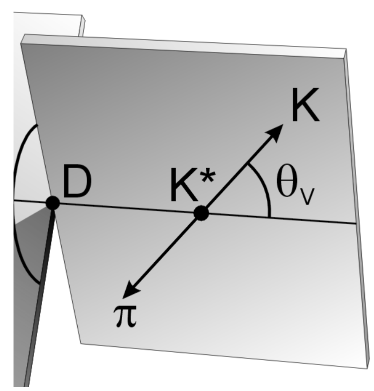
$$D^+ \to \overline{K}^{*0} m^+ n$$

$$\frac{d^5\Gamma}{dm_{kp}\, dq^2\, d\cos q_V\, d\cos q_\ell\, dc} \propto \left\{ \left| \begin{array}{c} \sin q_V (1+\cos q_\ell) e^{ic} B_{K^{*0}} H_+(q^2) \\ -\sin q_V (1-\cos q_\ell) e^{-ic} B_{K^{*0}} H_-(q^2) \\ -2\cos q_V \sin q_\ell B_{K^{*0}} H_0(q^2) \end{array} \right|^2 \right\}$$









Phys.Lett.B535:43-51, 2002
hep-ex/0203031

FOCUS added a term, things got better

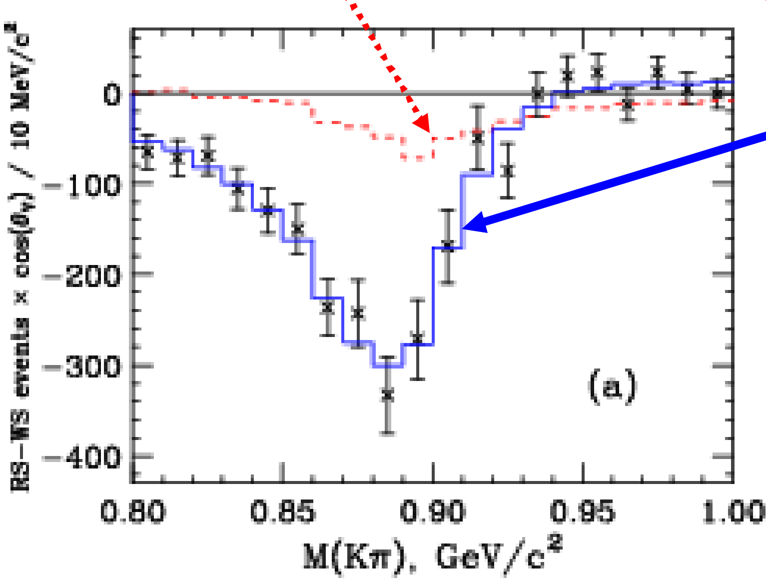
Signal Events weighted by avg($\cos q_V$):

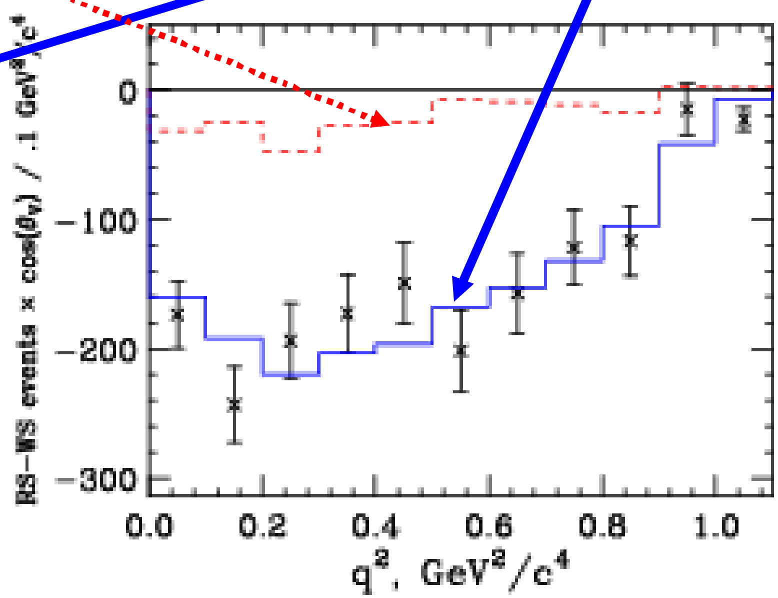
$$\frac{d^5\Gamma}{dm_{kp}\, dq^2 d\cos q_V\, d\cos q_\ell\, dc} \propto$$

$$\left\{ \left| \begin{array}{l} (1+\cos q_\ell)\sin q_V e^{ic} B_{K^{*0}} H_+(q^2) \\ -(1-\cos q_\ell)\sin q_V e^{-ic} B_{K^{*0}} H_-(q^2) \\ -2\sin q_\ell(\cos q_V B_{K^{*0}} + Ae^{id})H_0(q^2) \end{array} \right|^2 \right\}$$

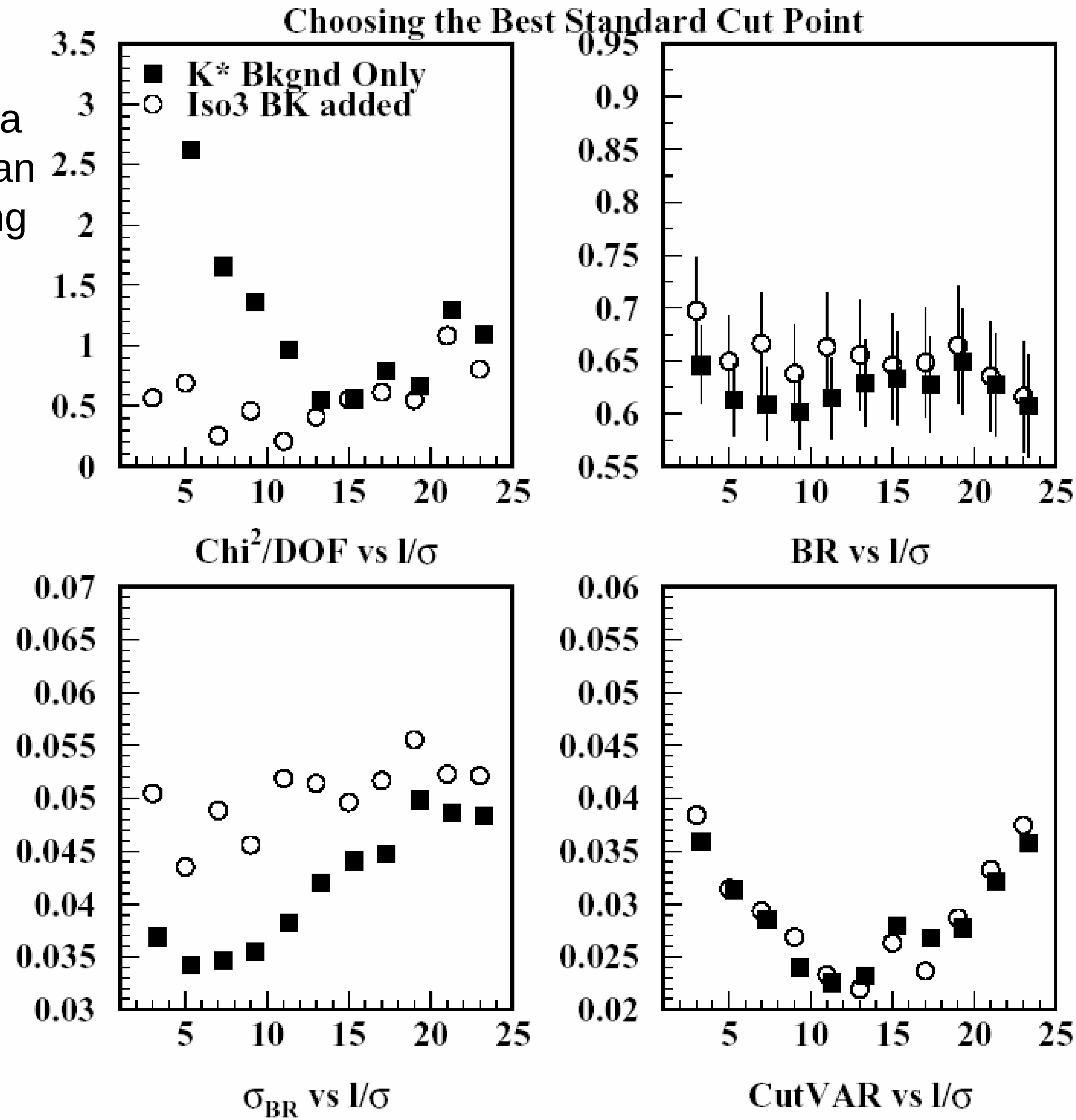
No added term

L=0 ansatz





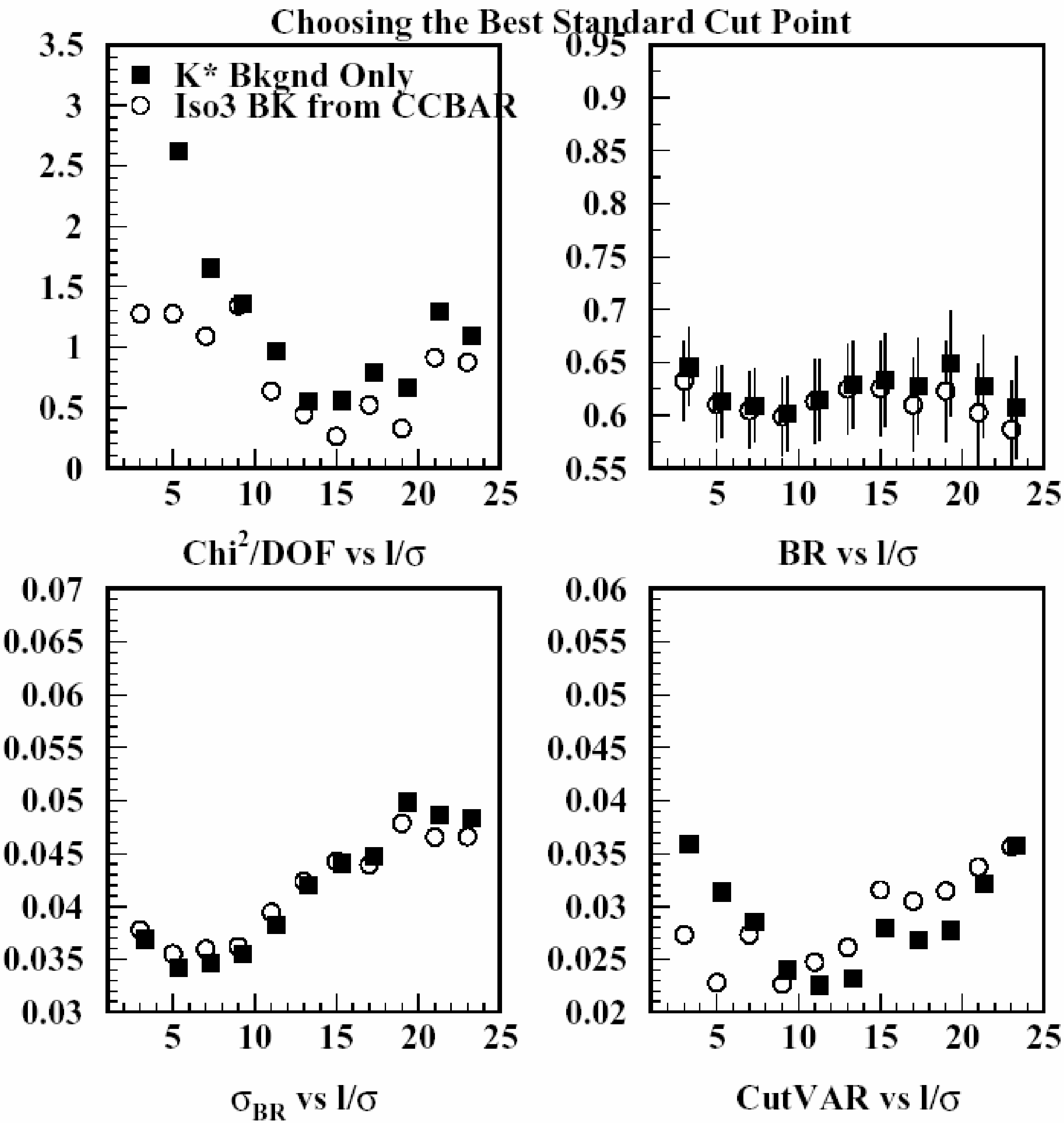
Here we are taking a background from the data where events likely had an extra track and comparing it to a background dominated by K*munu. (Which happens for sure when the signal is very clean)



The tighter you cut, the less statistics you have. But it’s worse here since the data based background has a small component of signal in it: we’ve correlated the signal and background in a bad way!

But you can get the same sort of background from the simulation. Since the majority of unmodelled junk occurs at low separation (l/sigma) we expect agreement to be better at higher separation.

Except in the simulation, we know when the signal is leaking into the background, so we can remove it *a-priori,* and the error “bonus” goes away!



Matrix Element Parameterization

$$M = \mathrm{G_F}\ V_{cs}\left[f_+(q^2)(p_D+p_K)^\sigma + f_-(q^2)(p_D-p_K)^\sigma\right](\overline{u}_\nu\gamma_\sigma(1-\gamma^5)u_\mu) \quad (1.5.6)$$

which leads to a decay rate in the D^0 center of mass:[15]

$$\frac{d^2\Gamma}{dE_K\ dE_\mu} = \frac{\mathrm{G_F}^2}{4\pi^3}|\ V_{cs}\ |^2$$
$$\Big(|\ f_+(q^2)\ |^2\Big[M_D(2E_\mu(M_D - E_\mu - E_K) - M_D(E_K^{max} - E_k))+$$
$$\frac{1}{4}M_\mu^2(E_K^{max} - E_k) - M_\mu^2(M_D - E_\mu - E_K)\Big]+$$
$$Re\{f_-(q^2)/f_+(q^2)\}\Big[M_\mu^2((M_D - E_\mu - E_K) - \frac{1}{2}(E_K^{max} - E_k))\Big]+$$
$$|\ f_-(q^2)\ |^2\Big[\frac{1}{4}M_\mu^2(E_K^{max} - E_k)\Big]\Big) \quad (1.5.7)$$

where we parameterize the form factors:

$$f_\pm(q^2) = \frac{f_\pm(0)}{1 - q^2/M_{D^*}^2},\ E_K^{max} = \frac{M_D^2 + M_K^2 - M_\mu^2}{2M_D} \quad (1.5.8)$$

and using the K^+ decay as an example we predict:

$$f_-(0)/f_+(0) = -\frac{M_D^2 - M_K^2}{M_{D^*}^2} = -0.7 \quad (1.5.9)$$

Evolution of the strong current

$$M = \mathrm{G_F}\ f_K\ (p_K + p_\pi)^\sigma \left[\frac{g^{\sigma\delta} - p^\sigma p^\delta / M_{K^*}^2}{q^2 - M_{K^*}^2}\right] (\overline{u}_\nu \gamma_\delta (1-\gamma^5)\gamma u_e) \qquad (1.5.1)$$

Assuming a massive propagator

which can be written:

$$M = \mathrm{G_F}\ \frac{f_K}{q^2 - M_{K^*}^2}\left[(p_K + p_\pi)^\sigma - \frac{M_K^2 - M_\pi^2}{M_{K^*}^2}(p_K - p_\pi)^\sigma\right](\overline{u}_\nu \gamma_\sigma (1-\gamma^5) u_e) \qquad (1.5.2)$$

A more general approach is usually taken where one defines the hadronic current in terms of the form factors f_+ and f_-:

$$M = \mathrm{G_F}\ \left[f_+(q^2)(p_K + p_\pi)^\sigma + f_-(q^2)(p_K - p_\pi)^\sigma\right](\overline{u}_\nu \gamma_\sigma (1-\gamma^5) u_e) \qquad (1.5.3)$$

and comparing to the parameterization (1.5.2):

$$\frac{f_-(0)}{f_+(0)} = -\frac{M_K^2 - M_\pi^2}{M_{K^*}^2} = -0.3 \qquad (1.5.4)$$